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Assessment of Contamination and Accumulation of Heavy Metals in Sediments of Lake Issyk-Kul

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Abstract

Issyk-Kul is one of the largest continental highland lakes, known for its considerable depth and unique water homogeneity. Due to its rich history, favourable environmental conditions and unique geographical location, the lake is of significant value for Kyrgyzstan. The present study assessed the levels of heavy metal pollution and their accumulation processes in the bottom sediments of the lake. Sediment samples were collected from six locations around the lake: Balykchy, Chok-Tal, Cholpon-Ata, Bosteri, Tyup and Ottuk. The concentrations of 16 heavy metals were analyzed using ICP-OES. Pollution factor (CF), geoaccumulation index (Igeo), degree of pollution (Cd) and pollution index (PLI) were calculated from the data. The sediments in most points were moderately contaminated, but significant contamination was detected in the Tyup area. The sediments of Cholpon-Ata showed a low level of chromium contamination, otherwise, they remained clean. Among the toxic elements, moderate contamination was found for Vanadium (V) and Chromium (Cr), while elements such as Co, Cu, Ni and Zn showed low levels of contamination. The results of the study confirm the necessity of continuous monitoring of heavy metal concentrations in the bottom sediments of Lake Issyk-Kul and putting in place measures to prevent their accumulation.

Keywords

Bottom sediments; Pollution load index; Geoaccumulation index; Pollution factor; Issyk-Kul Lake

Introduction

In recent decades, population growth, accelerated urbanization, and industrial development have increased the pressure on aquatic ecosystems around the world, including Issyk-Kul. Heavy metal pollution poses a particular threat to the ecosystem and human health due to its toxicity, resistance to decomposition and tendency to bioaccumulate. These metals, once in water bodies, are deposited in bottom sediments and can accumulate in living organisms, including fish, which in turn increases the risk of toxic substances entering the human food chain and causing damage to various organs and body systems. Studies confirm that rivers are the main route of heavy metals into water bodies (Mamun *et al.*, 2021). Since more than 80 rivers flow into Lake Issyk-Kul and there are no drains, the accumulation of pollutants, including heavy metals, becomes inevitable.

The rapid development of industry and tourism infrastructure on the lake's shores has increased pollution of surface water and bottom sediments, threatening the lake's ecosystem. Issyk-Kul serves as a vital habitat for diverse aquatic organisms and vegetation, with fisheries representing a major industry-highlighting the importance of assessing heavy metal accumulation within the food chain. Heavy metals can accumulate in sediments through physico-chemical processes such as dissolution, precipitation, sorption and complexation (Ardila *et al.*, 2023; Bakshe and Jugade, 2021; Haynes and Zhou, 2022). At the same time, studies aimed at assessing heavy metal pollution specifically in the bottom sediments of Lake Issyk-Kul were limited, as the main focus was on water quality analyses. Concentrations associated with suspended solids were determined indirectly as the difference between total and dissolved concentrations. With this approach, the reliability of chemical analyses of suspended solids is questionable. But in most aquatic systems, heavy metal concentrations in suspended solids and in the upper layers of bottom sediments are much higher than in the water column. The close association of some heavy metals (As, Cd, Hg, Pb, Zn) with seston and bottom sediments means that their distribution, geochemical migration and availability to hydrobionts cannot be correctly assessed by water sampling and soluble phase analyses alone (Dauwalter, 2005).

Studies on heavy metal content in the bottom sediments of Lake Issyk-Kul are limited, as previous analyses have primarily focused on water samples rather than sediment samples (Urmanbetov *et al.*, 2001). Earlier studies on pollution and heavy metal accumulation in Lake Issyk-Kul have focused on calculating parameters such as the contamination factor (CF), geoaccumulation index (Igeo), degree of contamination (Cd), and pollution load index (PLI). Heavy metal contamination in aquatic ecosystems has become a critical environmental concern due to its toxicity, persistence, and potential for bioaccumulation. Issyk-Kul Lake, being an ecologically sensitive and socioeconomically important water body, is potentially vulnerable to pollution from various anthropogenic activities such as agriculture, urban development, industrial processes, and transportation (Totubaeva *et al*., 2024). However, there is limited comprehensive data on the distribution and levels of heavy metals in the lake's bottom sediments. Identifying the sources and intensity of metal contamination is essential for developing appropriate management strategies. Therefore, this study addresses the need for systematic monitoring by analyzing heavy metal concentrations in bottom sediments

and calculating pollution indices to support effective environmental protection of Lake Issyk-Kul.

Materials and Methods

Study Area

Lake Issyk-Kul is a rainless body of water in arid Central Asia that plays a key role in maintaining environmental stability and socio-economic development in the region. Located at an altitude of 1,608 metres above sea level, the lake occupies a tectonic depression between the Kungei and Teskei Ala-Too ranges. It is the second largest high-altitude lake in the world, with a water surface of 6236 km² and a maximum depth of 668 metres. The lake is 178 km long and 60.1 km wide, with a water mineralisation of 6 - 6.5%, which determines its sulphate-sodium-magnesium composition (Asanova *et al.*, 2017).

Sampling Design

Bottom sediment samples were collected around Issyk-Kul Lake. A total of six sites were selected by the purposive sampling method (Taherdoost, 2016). In September 2023, sediment samples were collected from six locations in Lake Issyk-Kul following a standardized sampling protocol (Figure 1). Silt banks were selected at the sampling locations as silt is a good source of metal accumulation (Figure 2). Samples were collected from a depth of 0-12 cm and placed in plastic containers pre-treated with 10% nitric acid solution (HNO_3) and rinsed with distilled water to prevent contamination. During transport, the samples were stored in a refrigerator to preserve their properties. Sludge sediments were chosen for sampling because they have a high capacity to accumulate heavy metals due to the developed particle surface and organic matter content (Katanaeva *et al.*, 2003). In the laboratory, the samples were dried in an oven at 45 °C for 48 hours in a dust-free environment. The dried samples were then ground into powder using a pestle and mortar and sieved through a sieve with a mesh size of 2 mm to obtain a homogeneous mass. The prepared samples were stored in plastic containers until analyzed (Mamun *et al*. 2021).

Assessment of Sediment Quality

Heavy metals in lake sediments were analysed to measure the quality of the sediment. Parameters such as contamination factor (CF), degree of contamination (Cd), geoaccumulation index (Igeo) and pollution load index (PLI) were calculated to determine the level of contamination in lake sediments (Mamun *et al*., 2021).

Physicochemical Analysis of River Sediments

Standard methodology was used to determine pH and EC: sediment samples were mixed with distilled water and shaken thoroughly for 60 min. The mixture was allowed to stand for 60 minutes. Before measuring the pH, the suspension was re-stirred for 10 seconds. The pH and electrical conductivity (EC) were then measured using a Thermo Scientific Eutech pH 150 meter, as described by Suwannang (2021).

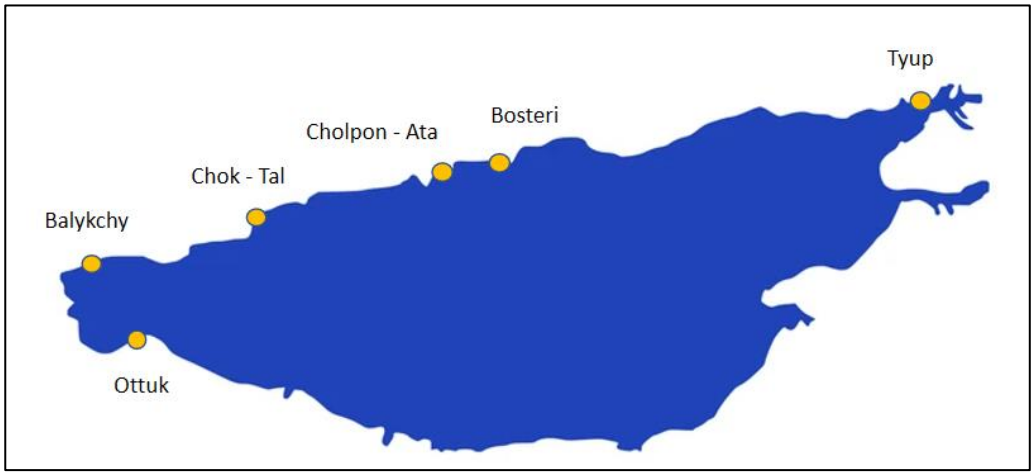

Figure 1: Study area and sampling locations

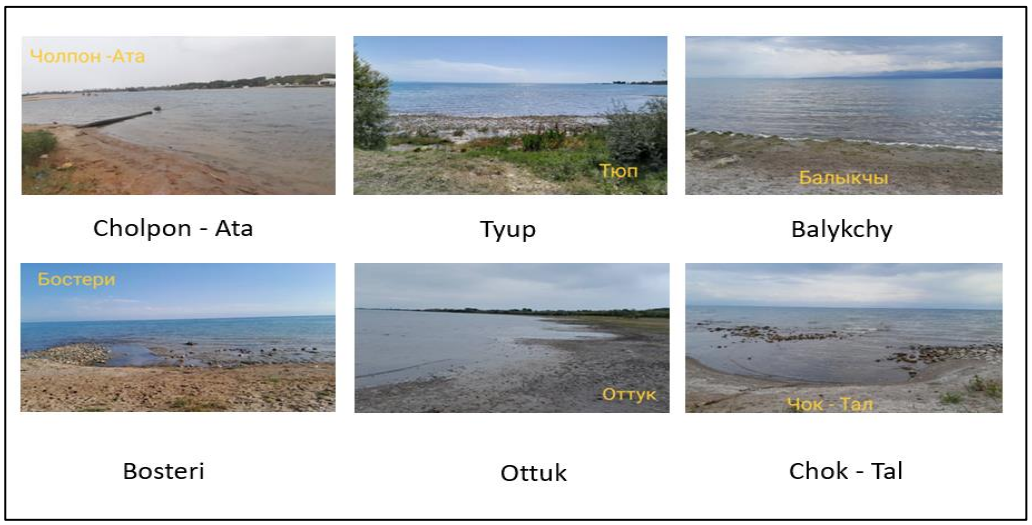

Figure 2: Shores selected for sampling.

Estimation of Heavy Metal Content in the Sludge

Heavy metals were analyzed using an ICP-OES (Optical Emission Spectrometer) Optima 5300DV. Manufacturer: PerkinElmer). The sediment was separated using a large sieve to remove large stones, pebbles and organic matter. The cleaned samples were then stored in acid-washed containers and dried in an oven at 105 °C for 24 h. The dried samples were thoroughly ground to a fine, homogeneous powder using an acid-washed pestle and mortar. Thereafter, 8 grams of the powdered sample were transferred into an acid-washed beaker, to which 2.5 mL of 65% concentrated HNO_3 and 7.5 mL of 37% concentrated $HClO_4$ were added. The beaker was then covered with a watch glass to prevent contamination and minimize acid loss during digestion. Some 500 ml of distilled water was added to each beaker when sufficiently cooled and placed in a 150 ^oC controlled temperature water bath for 3 hours (Hassan *et al*, 2015). The samples were then cooled to room temperature and filtered through a 0.45 µm membrane filter, and the concentration was determined by spectroscopy. The analyses were carried out at an

accredited laboratory. The methodology is based on standard protocols for acid digestion followed by ICP-OES.

Contamination Factor (CF)

Contamination Factor (CF) is a quantitative measure used to assess the level of heavy metal contamination in sediments by comparing the observed concentration of each metal to its background or reference value. (Mamun *et al*., 2021). The formula is as follows:

CF = Measured metal concentration/ Background concentration of the same metal (1)

To identify the background concentration, we tried to choose the area least affected by anthropogenic activities and the Balykchy area was chosen. This area is characterized by the lowest degree of anthropogenic impact compared to other studied areas. Historically, the Balykchy area has been subjected to less anthropogenic impact than other coastal areas of the lake. This area lacks large industrial enterprises, intensive agriculture, and significant sources of wastewater that could significantly affect the level of heavy metal pollution. The choice of Balykchy allows a correct comparative assessment of pollution levels in other parts of the lake. To determine the quality of sediments by pollution factor, the classification shown in table 1 was used.

Table 1: Classification of sediment quality by contamination factor (CF) (Hakanson, 1980)

CF values	*Class*	*Sediment quality*
CF < 1	1	Low CF
1 ≤ CF < 3	2	Moderate CF
3 ≤ CF < 6	3	Considerable CF
CF ≥ 6	4	Very high CF

Degree of Contamination (Cd)

The degree of pollution was calculated as the sum of all pollution factors. Cd is the degree of total contamination of surface layers at a particular sampling location, used as a diagnostic tool for pollution control:

$$Cd = \sum_{i=1}^{i=1} CF \quad (2)$$

The degree of contamination (Cd) was defined as the sum of all contamination factors. The following terminology was adopted to describe the degree of contamination (Cd values) for the selected metals, as presented in table 2.

Table 2: Classification of sediment quality by Cd (Mamun *et al*., 2021)

Cd< n	low pollution
n = Cd< 2n	moderate pollution
2n = Cd< 4n	severe pollution
Cd= 4n	very high degree of pollution, indicating severe anthropogenic pollution

(n = number of elements)

Geoaccumulation Index (Igeo)

When assessing aquatic toxicity, the geoaccumulation index (Igeo) matrix could be applied to assess sedimental contamination. Igeo values for sediment are calculated using the equation:

$$I_{geo} = Log_2[\frac{C_n}{(1.5 \times B_n)}] \quad (3)$$

Where Cn is the concentration of element n in the sediment and Bn is the geochemical context for element n, which is either measured in pre-civilization sediments of the area or taken from the literature (Mamun *et al.,* 2021). Based on Igeo, sediments can be classified into seven classes (Table 3).

Table 3: Igeo classification of sediment quality (Mamun *et al*., 2021)

I-geo Values	*Class*	*Sediment Quality*
≤ 0	0	Unpolluted
0-1	1	Unpolluted to moderately polluted
1-2	2	Moderately polluted
2-3	3	Moderately to strongly polluted
3-4	4	Strongly polluted
4-5	5	Strongly to extremely polluted
≥ 6	6	Extremely polluted

Pollution Load Index (PLI)

The Pollution Load Index (PLI) determines the amount of an element in the environment. The PLI value reflects the sediment metal toxicity level. The PLI of an individual site is the nth degree root of the nth power of the multiplied pollution factor (CF) values. The PLI classification of sediments is given in Table 4.

$$PLI = (CF_1 \times CF_2 \times CF_3 \times \ldots CF_n)^{1/n} \quad (4)$$

Table 4: PLI classification of sediment quality (Mamun *et al.* 2021)

PLI=0	indicates perfection
PLI=1	indicates the presence of only baseline levels of pollutants
PLI>1	indicates a progressive deterioration in the quality of the site

Results

The concentrations of 16 metals were determined by analyzing the samples using a spectrometer. The results are presented in table 5.

Table 5a: Metal concentrations obtained from the spectrometer (ppm)

Area	*Mg*	*Mn*	*Mo*	*Na*	*Ni*	*Si*	*V*	*Zn*
Balykchy	22.921	0.165	0.034	59.162	0.011	11.901	0.013	0.020
Tyup	8.470	0.180	0.013	29.223	0.010	43.842	0.049	0.026
Ottuk	44.808	0.273	0.045	255.85	0.020	19.801	0.021	0.020
Bosteri	9.900	0.177	0.022	25.707	0.011	32.284	0.026	0.024

Area	*Mg*	*Mn*	*Mo*	*Na*	*Ni*	*Si*	*V*	*Zn*
Cholpon-Ata	12.001	0.043	0.025	54.815	<0.005*	3.689	<0.006*	0.009
Chok-Tal	10.532	0.167	0.007	39.029	0.012	38.579	0.036	0.044

Table 5b: Metal concentrations obtained from the spectrometer (ppm)

Area	*Al*	*Ba*	*Ca*	*Co*	*Cr*	*Cu*	*Fe*	*K*
Balykchy	3.813	0.140	63.558	0.006	<0.008*	0.045	2.282	12.602
Tyup	20.316	0.174	13.711	0.007	0.023	0.025	13.500	9.675
Ottuk	8.903	0.148	80.537	0.009	0.010	0.037	4.650	26.582
Bosteri	13.197	0.135	29.369	0.006	0.013	0.046	8.175	9.788
Cholpon-Ata	1.255	0.073	50.322	<0.004*	<0.008*	0.007	0.842	5.321
Chok-Tal	18.162	0.156	22.830	0.006	0.022	0.027	11.986	10.749

*****With '<' ICP-OES cannot detect the exact concentration because it is very low

Contamination factor (CF)

The calculation of CF., as presented in Table 6, indicates that Al, Fe, and V are the most significant contributors to sediment contamination in the study area. These elements recorded the highest CF values, suggesting considerable to very high contamination levels, particularly for Al and Fe. Chromium (Cr) and V exhibited moderate contamination, highlighting their potential environmental concern and the need for regular monitoring. In contrast, the contamination levels for Zn, Ni, Co, Cu, and Mo remained within low contamination categories, indicating limited anthropogenic influence or effective natural attenuation processes for these metals. These findings are visually represented in Figure 3, which clearly illustrates the variation in contamination levels among the studied heavy metals, underscoring the spatial heterogeneity and differing sources or mobilities of these elements within the sediment environment. The high levels of iron can be explained by the geological structure of the region, where iron ores often contain aluminum and vanadium, indicating a natural source of their content. The CF chromium and vanadium contamination factor by ArcGIS mapping software represented in figure 4.

Table 6a: Results of the pollution factor (CF) calculation (ppm)

CF	*Al*	*Ba*	*Ca*	*Co*	*Cu*	*Na*	*Fe*	*V*
Tyup	5.328	1.24	0.216	1.167	0.556	0.494	5.916	3.77
Ottuk	2.335	1.057	1.267	1.5	0.813	4.325	2.038	1.615
Bostery	3.44	0.964	0.462	1	1.023	0.435	3.582	2
Cholpon - Ata	0.329	0.52	0.79	0.667	0.156	0.927	0.37	0.46
Chok - Tal	4.763	1.11	0.359	1	0.056	0.66	5.252	2.77

Table 6b: Results of the pollution factor (CF) calculation (ppm)

CF	*K*	*Mg*	*Cr*	*Mn*	*Mo*	*Ni*	*Si*	*Zn*
Tyup	0.768	0.37	2.875	1.09	0.382	0.9	3.68	1.3
Ottuk	2.1	1.95	1.25	1.655	1.324	1.8	1.66	1
Bostery	0.77	0.43	1.625	1.073	0.647	1	2.7	1.2

CF	*K*	*Mg*	*Cr*	*Mn*	*Mo*	*Ni*	*Si*	*Zn*
Cholponata	0.42	0.524	1	0.26	0.735	0.45	0.3	0.45
Chok - Tal	0.8	0.46	2.75	1.012	0.2	1.09	3.24	2.2

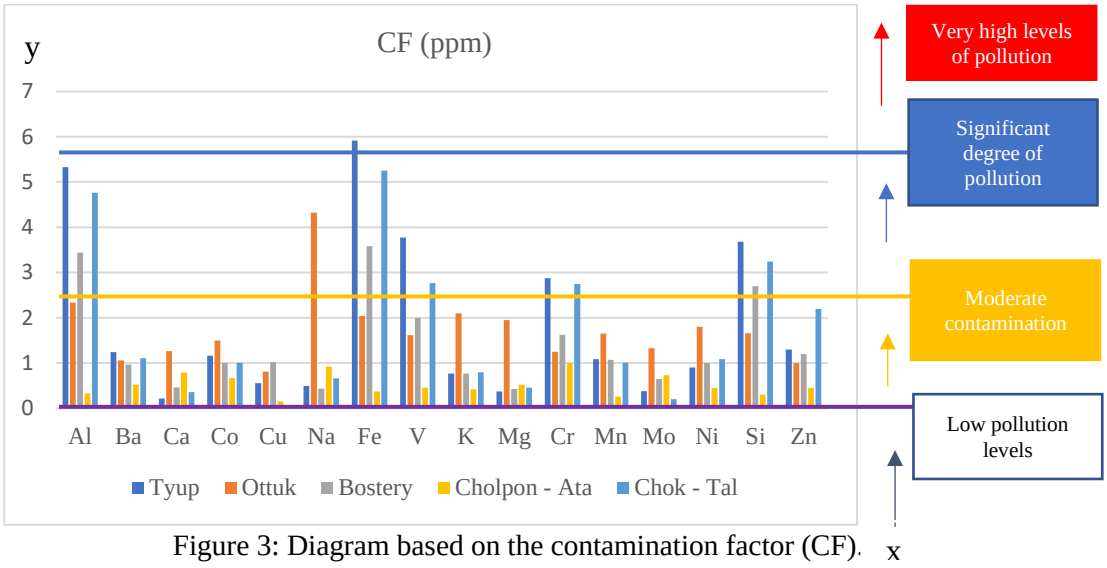

Figure 3: Diagram based on the contamination factor (CF).

The bars of the diagram (Figure 3) denote the metal contamination factor in a particular location. The higher the bar, the higher the contamination. Horizontal lines indicate the range and level of contamination, and on the right side of the chart are written the levels of contamination. On the x-axis are the sampling locality and metals, and on the y-axis is the CF value.

Figure 4: CF chromium and vanadium contamination factor by ArcGIS mapping software.

Pollution Degree (Cd)

According to the results of the pollution degree (Cd) calculations (Table 7 and Figure 5), Tyup emerged as the most polluted site, with values approaching the threshold for

significant pollution. This suggests a higher cumulative presence of heavy metals in the sediments of this area, potentially due to upstream industrial, agricultural, or urban runoff. Moderate pollution levels were identified in the regions of Chok-Tal, Ottuk, and Bosteri, indicating a noticeable but less severe accumulation of contaminants. These areas may be influenced by mixed pollution sources or less intensive human activities. The least polluted location was found to be Cholpon-Ata, where the degree of contamination remained low, reflecting minimal anthropogenic input or effective natural buffering processes in the sediment environment. These findings highlight the spatial variability in sediment pollution across the Issyk-Kul Lake region and underscore the need for site-specific management strategies to mitigate heavy metal contamination. This distribution is related to the number of rivers flowing into the lake in each territory. Water coming from highland rivers brings agricultural and industrial wastes, as well as chemical elements from natural sources, into the lake.

Table 7: Results of calculations of pollution degree (Cd) (ppm).

Area	*Cd*
Tyup	30.052
Ottuk	27.699
Bostery	22.371
Cholpon - Ata	8.358
Chok - Tal	27.722

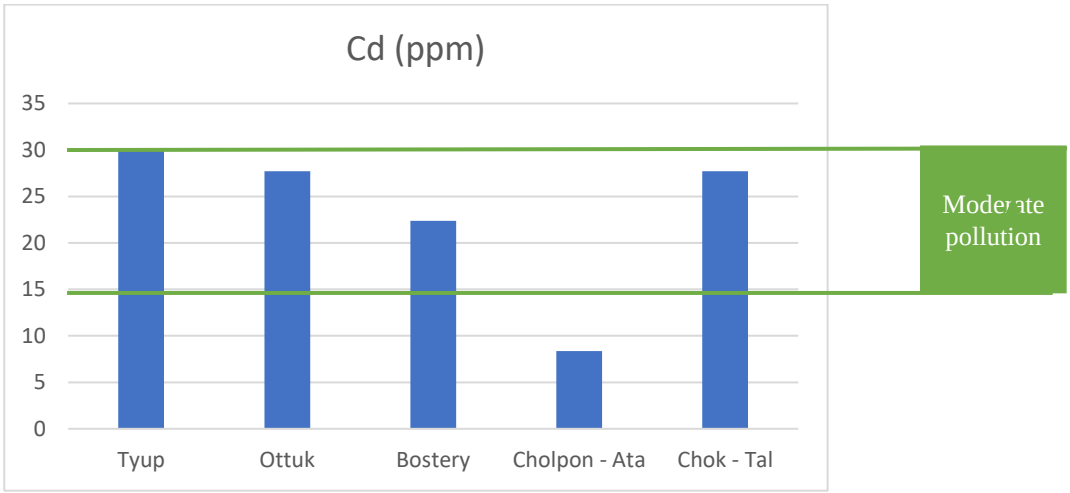

Figure 5: Diagram based on the degree of contamination (Cd)

Table 8: Classification of the degree of contamination (Cd) in our data, i.e. n = 16

Cd< 16	low contamination
16 = Cd< 32	moderate contamination
32 = Cd< 64	significant contamination
Cd = 64	very high degree of contamination, indicating serious anthropogenic pollution

The classification of Cd data (Table 8) indicates clear spatial differences in pollution

levels across the studied sites. Tyup stands out as the most polluted area, with Cd values approaching the threshold for serious pollution. The areas of Chok-Tal, Ottuk, and Bosteri fall under the category of moderately polluted. In contrast, Cholpon-Ata is classified as the least polluted or unpolluted site, indicating minimal heavy metal input and relatively good environmental quality of sediments in this region. This distribution can be explained by the fact that in each locality, a certain number of rivers flow into the lake. Issyk-Kul is fed by many high-mountain rivers. Wastes from agriculture, industry and residential areas are discharged into the rivers. Natural sources of metals should not be excluded. Mountains are rich in various elements, including metals. Rivers serve as the primary pathway for the transport of metals, acting as conduits that carry contaminants from various anthropogenic sources. But Lake Issyk-Kul is a drainless lake, so it is not capable of self-purification. The degree of pollution of Issyk-Kul Lake areas according to the ArcGIS mapping programme is demonstrated in Figure 5.

Figure 5: Degree of pollution of Issyk-Kul Lake areas according to the ArcGIS mapping programme

As shown in figure 6, Tyup, Chok-Tal and Bosteri - areas with a medium level of metal pollution - are highlighted in red. In these areas, many rivers that transport metals flow into the lake. At the same time, significantly fewer rivers flow into Cholpon-Ata and Ottuk. Cholpon-Ata remains virtually unpolluted, while Ottuk is moderately polluted and close to significant levels of pollution. This can be explained by the fact that the coastal zones of Ottuk contain a lot of organic sediments, as a significant part of the area is silt. In addition, the active agricultural activities prevalent in the area also contribute to the pollution of Ottuk. Due to the lack of quantitative data on local sources, the contribution of anthropogenic and natural factors is assessed qualitatively. The potential risks of bioaccumulation of metals through sediments to aquatic organisms are highlighted as an important area for future research.

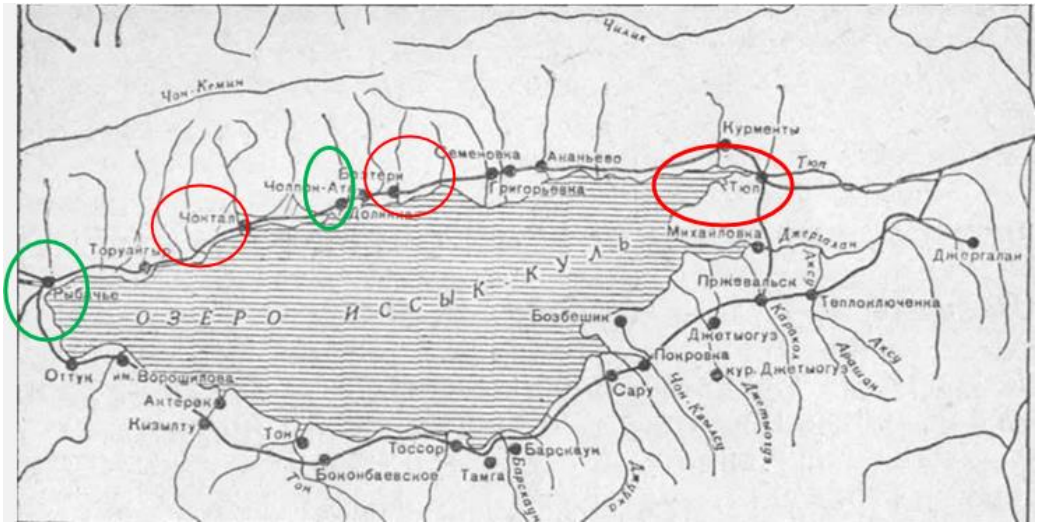

Figure 6: Map of Lake Issyk-Kul and the rivers flowing into it

Geoaccumulation Index (Igeo)

The geoaccumulation index showed (Table 9, Figure 7) that Tyup, Chok-Tal and Bosteri have moderate levels of aluminium pollution, while Ottuk and Tyup have high levels of sodium and vanadium pollution, respectively. Cholpon-Ata remains unpolluted. These indicators show the diversity of anthropogenic and natural sources of metals in different areas of the lake.

Table 9a: Results of the calculation of the geo-accumulation index (Igeo)

Igeo	*Al*	*Ba*	*Ca*	*Co*	*Cu*	*Na*	*Fe*	*V*
Tyup	1.829	-0.271	-2.837	-0.358	-1.434	-1.599	1.978	1.322
Ottuk	0.639	-0.515	-0.252	0	-0.862	1.526	0.444	0.098
Bostery	1.202	-0.644	-1.737	-0.578	-0.556	-1.786	1.257	0.422
Cholpon - Ata	-2.322	-1.515	-0.916	-1.152	-3.322	-0.69	-2	-1.737
Chok - Tal	1.632	-0.434	-2.059	-0.578	-1.322	-1.184	1.807	0.888

Table 9b: Results of the calculation of the geo-accumulation index (Igeo)

Igeo	*K*	*Mg*	*Cr*	*Mn*	*Mo*	*Ni*	*Si*	*Zn*
Tyup	-0.971	-2	0.926	-0.454	-2	-0.737	1.299	-0.206
Ottuk	0.485	0.379	-0.269	0.138	-0.184	0.275	0.138	-0.585
Bostery	-0.943	-1.786	0.111	-0.515	-1.218	-0.578	0.848	-0.322
Cholpon - Ata	-1.837	-1.515	-0.578	-2.556	-1.029	-1.737	-2.322	-1.737
Chok - Tal	-0.811	-1.737	0.872	-0.578	-2.837	-0.454	1.07	0.553

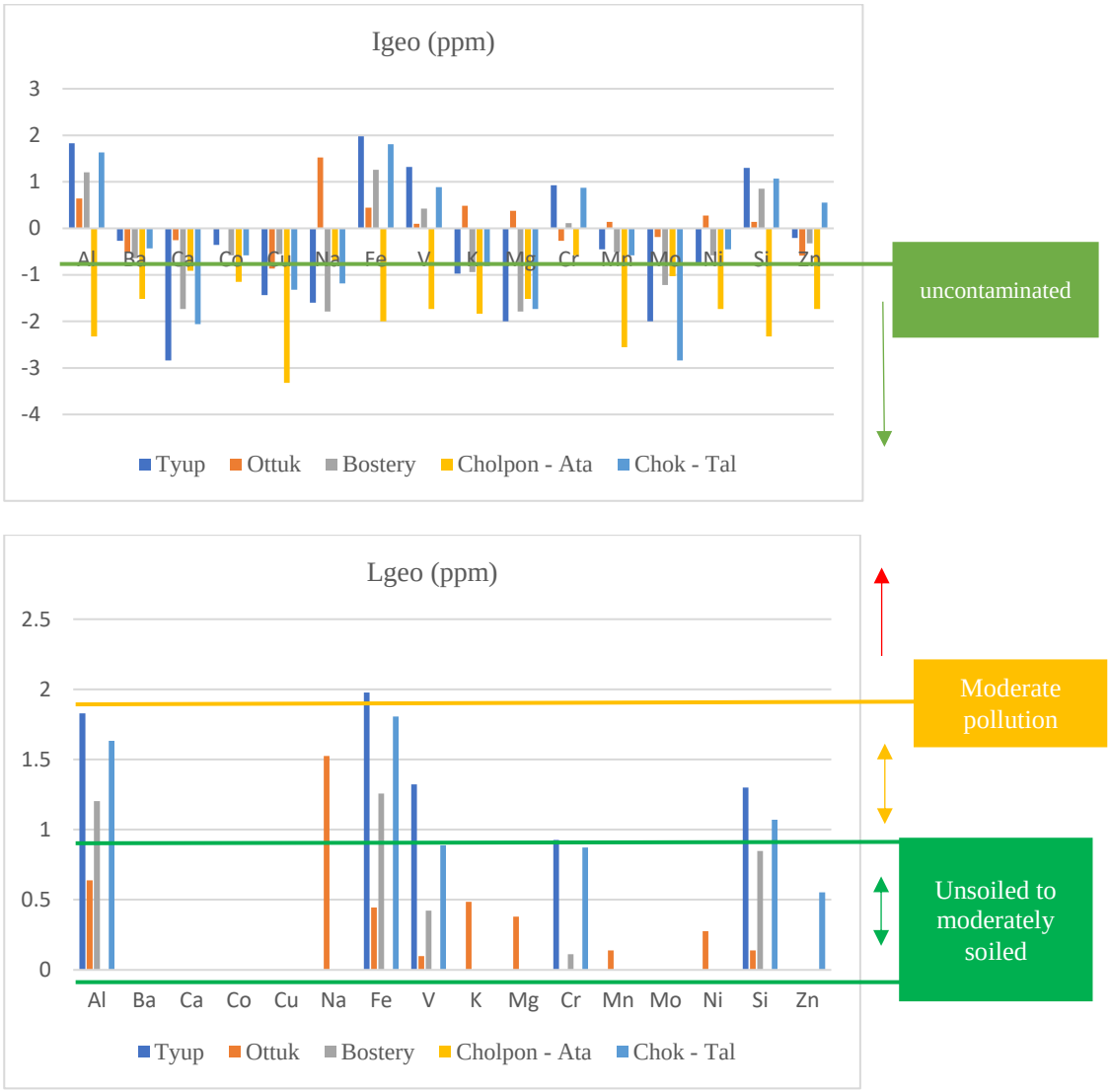

Figure 7: Diagram based on geoaccumulation index (Igeo)

According to the geoaccumulation index in Tyup, Chok-Tal and Bosteri, aluminium is in the medium range of pollution. In Ottuk - sodium and in Tyup - vanadium at high pollution levels.

Tyup: Fe, Al, V, Si, Cr.
Ottuk: Na, Al, K, Fe, Mg, Ni, Si, Mn, V.
Bosteri: Fe, Al, Si, V, Cr.
Chok -Tal: Fe, Al, Si, V, Cr, Zn.
Cholpon-Ata is unpolluted.

Most of the metals are in the range of uncontaminated to moderately contaminated level. Except for Cholpon-Ata, which is uncontaminated. In Figure 8 one can visually assess the Igeo of chromium and vanadium.

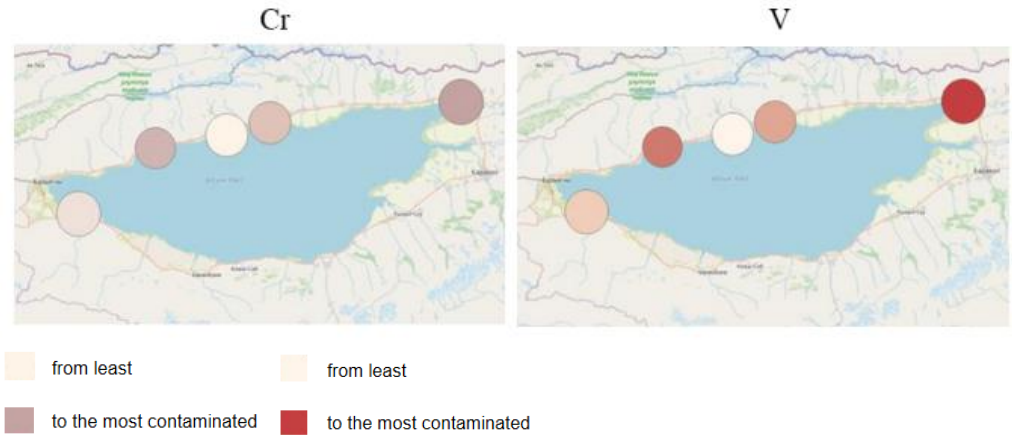

Figure 8: I_{geo} geo-accumulation index of chromium and vanadium by the ArcGIS programme

Pollution Load Index (PLI)

According to the Pollution Load Index (PLI) (Table 10), the majority of Lake Issyk-Kul localities are prone to deterioration of environmental quality (Figure 9). At the same time, the environmental quality in the Cholpon-Ata area remains at an optimal level. High PLI values are associated with anthropogenic impact as well as natural features of the geological structure of the region, such as high iron and vanadium content.

Table 10: Results of the pollution load index (PLI) calculation (ppm)

Area	*PLI*
Tyup	1.18
Ottuk	1.6
Bostery	1.12
Cholpon - Ata	0.47
Chok - Tal	1.03

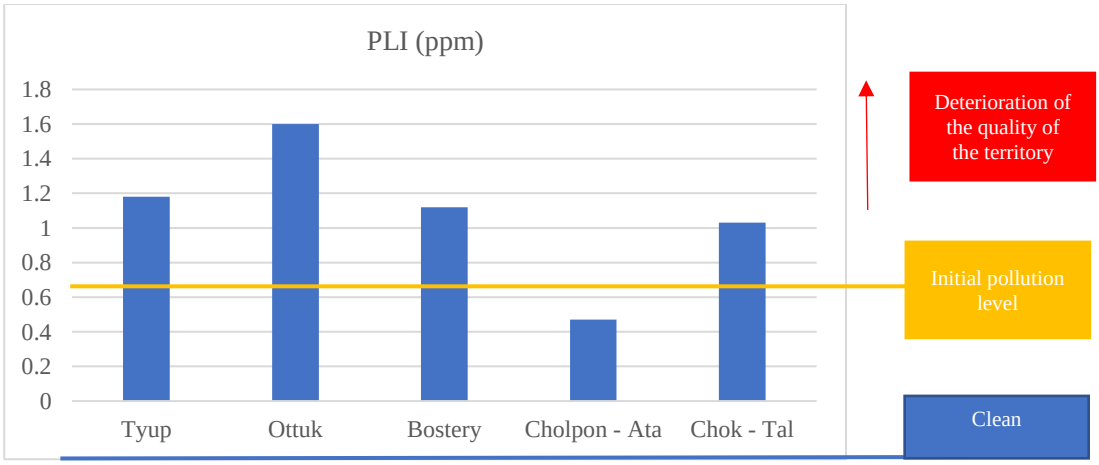

Figure 9: Diagram based on pollution load index (PLI)

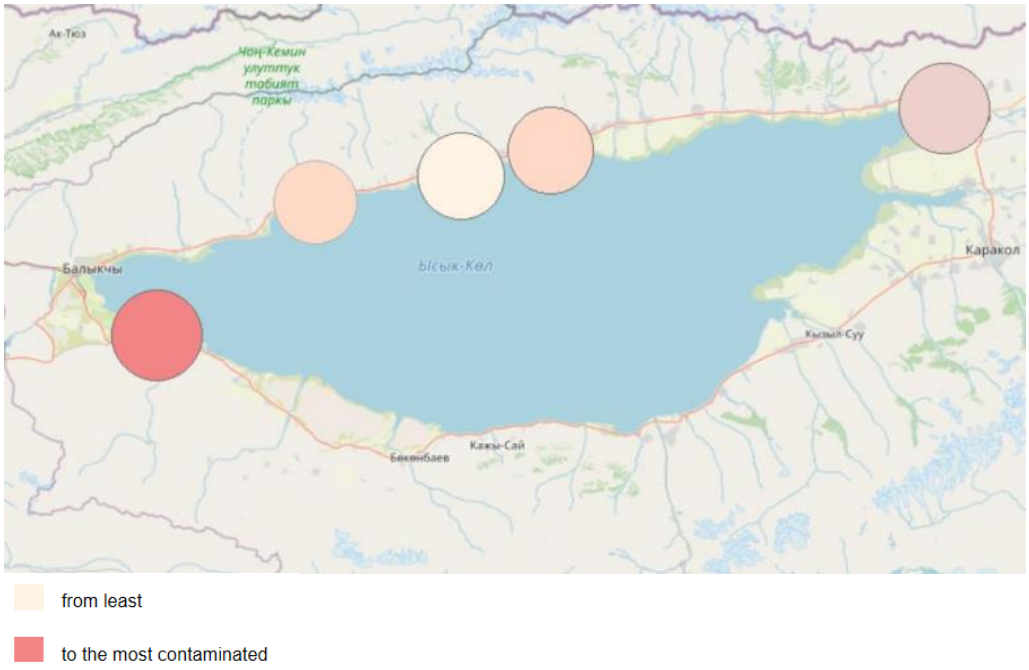

Figure 10: PLI pollution load index of Issyk-Kul Lake localities according to the ArcGIS mapping programme

As shown in figure 10, the highest PLI is observed in Ottuk. The lowest PLI is observed in Cholpon-Ata, which is the only area that is not polluted.

Physico-Chemical Characteristics of Sediments of Issyk-Kul Lake

The pH, electrical conductivity (EC) levels of Issyk-Kul Lake sediments were found within the range of EC = 329 - 3651 MS (Table 11), pH = 8.12 - 8.44 (Table 12).

Table 11: Electrical conductivity of bottom sediments (MS)

Area	*EC*
Balykchy	1551
Tyup	470
Ottuk	3651
Bosteri	482
Cholpon-Ata	1136
Chok-Tal	556

High electrical conductivity of water may favour the dissolution of heavy metals. If water has high electrical conductivity, it may contain more metal ions, which can be harmful to human health and the ecosystem as a whole. As depicted in figure 11, Ottuk has the highest electrical conductivity.

Doi: https://doi.org/10.33002/nr2581.6853.080137 Open Access

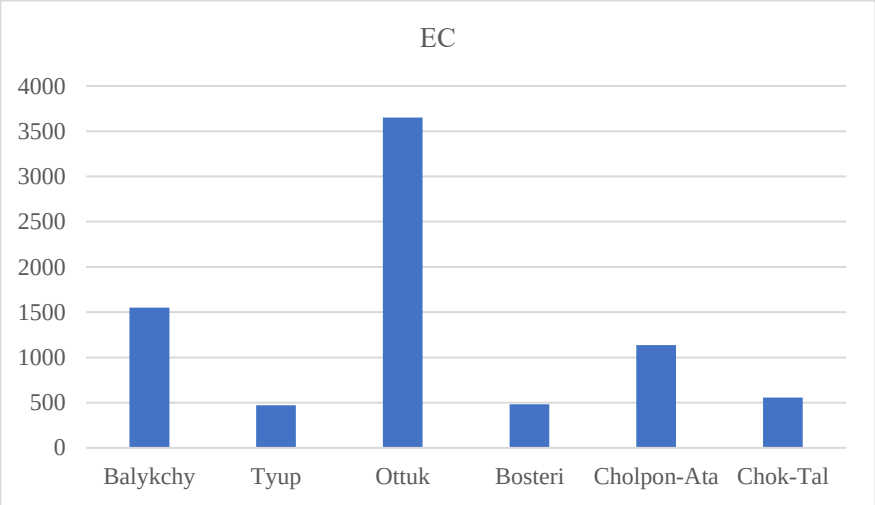

Figure 11: Diagram based on the electrical conductivity of heavy metals in the bottom sediments of Lake Issyk-Kul

Table 12: pH of bottom sediments

Area	*pH*
Balykchy	8.12
Tyup	8.37
Ottuk	8.13
Bosteri	8.44
Cholpon-Ata	8.14
Chok-Tal	8.34

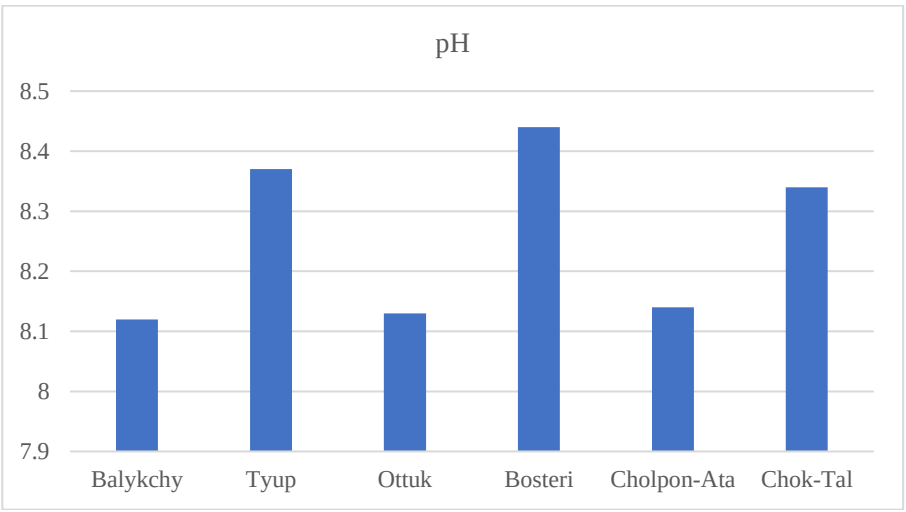

Figure 12: Diagram based on pH of heavy metals in the bottom sediments of Issyk-Kul Lake

As a result of the analysis, the pH of bottom sediments of Issyk-Kul Lake is known, which is in the range of 8.12 - 8.44, slightly alkaline environment (Table 12, Figure 12).

The pH affects the deposition of metals. In a slightly alkaline environment Pb, Hg, Cd, Cu, Fe and Al are less likely to precipitate. Zn and Ni are well precipitated (Papina, 2001). In alkaline waters metal salts in the process of complexation form metal hydroxides. Complexation reduces the toxicity of metals and is less susceptible to bioaccumulation, which also favourably affects the lake ecosystem. Forms occurring in a slightly alkaline environment are characterised by very low solubility. This favours the removal of heavy metal ions from the aqueous phase into the silt, given the pH value of surface water (6.5 - 8.5). Hydroxocomplexes, sulphide and carbonate complexes are widespread in the bottom sediments of Issyk-Kul Lake (Papina, 2001).

Discussion

The results showed that the lake environment is slightly alkaline, which favours low toxicity of metals and reduced mobility of metals. Calculations of pollution indices showed that the areas of Tyup, Ottuk, Chok-Tal and Bosteri are in the range of moderate pollution, with Tyup being close to the level of serious pollution. Cholpon-Ata, by all indicators, was the least polluted. This distribution is explained by the number of rivers flowing into the lake, carrying both natural and anthropogenic elements. Areas with higher pollution, such as Tyup, Bosteri, and Chok-Tal, have more tributaries, while Cholpon-Ata and Ottuk have fewer rivers flowing in. Additionally, high organic matter along the banks in Ottuk contributes to metal accumulation, a factor also noted in other lake studies (Ramal and Ghalib, 2023). Industrial emissions, agricultural runoff, and vehicular emissions contribute to contamination. Heavy metals from fertilisers and pesticides often enter the lake through surface runoff or groundwater (Karki and Verma, 2021). Iron, aluminium, and vanadium were found widespread across the lake, with moderate pollution levels for vanadium, chromium, zinc, and cobalt. The high concentration of iron and vanadium is linked to the region's geological features, as these metals are abundant in iron ores. However, anthropogenic factors also play a significant role, with chromium, copper, and nickel originating from industrial emissions, non-ferrous metallurgy, and pesticide use (Karki and Verma, 2021).

The geoaccumulation index revealed the following metal distributions:

Tyup: Fe, Al, V, Si, Cr
Ottuk: Na, Al, K, Fe, Mg, Ni, Si, Mn, V
Bosteri: Fe, Al, Si, V, Cr
Chok-Tal: Fe, Al, Si, V, Cr, Zn
Cholpon-Ata remained unpolluted.

According to the pollution load index, Ottuk is considered moderately polluted, followed by Tup, Bosteri and Chok-Tal, indicating moderate environmental and health impacts. These findings are consistent with the results of other studies of lakes where moderate to severe pollution was observed (Ramal and Ghalib, 2023). The use of indices like CF, Igeo, and PLI is crucial for understanding contamination risks. Effective management strategies can mitigate the impact of heavy metal pollution, as shown in recent global studies (Lui *et al*., 2023). In conclusion, Issyk-Kul's ecological status requires enhanced monitoring, control of emissions from tributaries, and improved waste management strategies to reduce the anthropogenic impact.

Conclusion

This study provides a comprehensive assessment of heavy metal contamination in the bottom sediments of Issyk-Kul Lake, highlighting both the spatial distribution and potential ecological implications of metal pollutants. The findings indicate that while the overall environment of the lake remains slightly alkaline, favouring reduced metal toxicity and mobility, several areas, particularly Ottuk, Tyup, Bosteri, and Chok-Tal, exhibit moderate levels of pollution. The presence of metals such as iron, aluminum, vanadium, chromium, and zinc reflects both natural geological influences and anthropogenic pressures, including industrial activity, agricultural runoff, and atmospheric deposition.

The application of pollution indices such as CF, Cd, Igeo, and PLI allowed for an objective evaluation of contamination levels and helped identify localised hotspots of concern. Cholpon-Ata stood out as the least polluted site, while Ottuk showed the highest cumulative pollution load. Given the ecological, cultural, and economic importance of Issyk-Kul Lake, these findings underscore the urgent need for enhanced environmental monitoring, stricter regulation of pollutants entering the lake from surrounding catchments, and improved waste and emission management. Future studies should incorporate temporal trends, metal speciation, and biological assessments to fully understand the long-term risks to the lake ecosystem and public health. Proactive measures will be vital to preserve the ecological integrity of this unique aquatic environment. To minimize sediment pollution, it is recommended to upgrade sewage treatment facilities in key areas, strengthen the control of agricultural and industrial effluents, and introduce principles of sustainable management of tourism infrastructure along the coast.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	*Author 1*	*Author 2*	*Author 3*
Conceived and designed the research or analysis	Yes	No	Yes
Collected the data	Yes	No	No
Contributed to data analysis & interpretation	Yes	Yes	Yes
Wrote the article/paper	Yes	Yes	Yes
Critical revision of the article/paper	Yes	No	No
Editing of the article/paper	No	Yes	Yes
Supervision	No	Yes	Yes
Project Administration	No	Yes	Yes
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